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Flash flood forecasting, warning and risk management: the HYDRATE project

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ABSTRACT

The management of flash flood hazards and risks is a critical component of public safety and quality of life. Flash-floods develop at space and time scales that conventional observation systems are not able to monitor for rainfall and river discharge. Consequently, the atmospheric and hydrological generating mechanisms of flash-floods are poorly understood, leading to highly uncertain forecasts of these events. The objective of the HYDRATE project has been to improve the scientific basis of flash flood forecasting by advancing and harmonising a European-wide innovative flash flood observation strategy and developing a coherent set of technologies and tools for effective early warning systems. To this end, the project included actions on the organization of the existing flash flood data patrimony across Europe. The final aim of HYDRATE was to enhance the capability of flash flood forecasting in ungauged basins by exploiting the extended availability of flash flood data and the improved process understanding. This paper provides a review of the work conducted in HYDRATE with a special emphasis on how this body of research can contribute to guide the policy-life cycle concerning flash flood risk management.

1. Introduction

The occurrence of flash flooding is of concern in hydrologic and natural hazards science due to the top ranking of such events among natural disasters in terms of both the number of people affected globally and the proportion of individual fatalities. Jonkman (2005) examined data from a large number of flood events over each continent, which occurred between January 1975 and June 2002, showing that flash floods out of that sample caused around 1550 casualties per year. Moreover, the study showed that flash flood mortality (computed as the number of fatalities divided by the number of affected persons) is higher than that for other natural hazards. The potential for flash flood casualties and damages is also increasing in many regions due to the social and economic development, which imply pressure on land use. Furthermore, evidence of increasing heavy precipitation at regional (Groisman et al., 2004) and global scales (Groisman et al., 2005; Beniston, 2009) supports the view that the global hydrological cycle is intensifying as a result of global warming (Huntington, 2006). Consequently, the flash flood hazard is expected to increase in frequency and severity, through the impacts of global change on climate, severe weather in the form of heavy rains and river discharge conditions (Kleinen and Petschel-Held, 2007; Beniston et al., 2011).

The high risk potential of flash floods is related to their rapid occurrence and to the spatial dispersion of the areas which may

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be impacted by these floods. Both characteristics limit our ability to issue timely flood warnings. Indeed, the sudden nature of the response is a characterizing feature of flash floods. In the USA flash floods are regarded as having a time to peak up to 6 h for catchments up to 400 km^2 (Georgakakos and Hudlow, 1984). Marchi et al. (2010) showed that this definition may apply to the Mediterranean and Continental areas of Europe as well. Flash floods are therefore associated with short, high-intensity rainfall rates, mainly of convective origin that occur locally. Runoff rates often far exceed those of other flood types due to the rapid response of the catchments to intense rainfall, modulated by soil moisture and soil hydraulic properties.

The small spatial and temporal scales of flash floods, relative to the sampling characteristics of conventional rain and discharge measurement networks, make also these events particularly difficult to observe and to predict (Borga et al., 2008). In an investigation of twenty-five major flash floods that occurred in Europe in the last twenty years, Marchi et al. (2010) showed that less than one half of the cases were properly documented by conventional stage measurements. In many cases, the rivers were either ungauged or the streamgauge structures were damaged by the event. Similar considerations apply to the rainfall estimation, as the spatial and temporal scales of the events are generally much smaller than the sampling potential offered by even supposedly dense raingauge networks (Anagnostou et al., 2006).

Flash floods, therefore, place the problem of ungauged basin prediction under rather extreme conditions. Process understanding is required for flash-flood risk management, because the dominant processes of runoff generation may change with the increase of storm severity, and therefore, the understanding based on analysis of moderate floods may be questioned when used for forecasting the response to extreme storms (Blöschl and Zehe, 2005; Collier, 2007). However, process understanding and learning from past events is hampered by the observational difficulties of flash floods.

In order to better understand the hydro-meteorological processes leading to flash floods, the EU Project HYDRATE was established. The full title of the project is "*Hydrometeorological Data Resources and Technology for Effective Flash Flood Forecasting*" – www.hydrate.tesaf.unipd.it. The primary objective of this project is to improve the scientific basis of flash flood forecasting by extending the understanding of past flash flood events, advancing and harmonising a European-wide innovative flash flood observation strategy and developing a coherent set of technologies and tools for effective early warning systems. To this end, the project includes actions on the organization of the existing flash flood data patrimony across Europe. The observation strategy proposed in HYDRATE has the objective to collect flash flood data by combining hydrometeorological monitoring and the acquisition of complementary information from post-flood surveys. This involves a network of existing Hydrometeorological Observatories, all placed in high flash flood potential regions. The final aim of HYDRATE was to enhance the capability of flash flood forecasting in ungauged basins by exploiting the extended availability of flash flood data and the improved process understanding. Work began in September 2006 and was completed by September 2010, bringing together a multidisciplinary team of 17 partner organizations from ten EU countries, China, USA and South Africa. HYDRATE developed a freely accessible European Flash Flood Database to make available the collected hydrometeorological data to the international research community. Research results and dissemination activities are documented in 93 peer-reviewed articles published in high-impact international journals, 7 book chapters and a large amount of public press appearances including TV, radio and newspapers. The HYDRATE team has recently completed a special issue published in the Journal of Hydrology entitled "*Flash flood: observations and analysis of hydrometeorological controls*" (Borga et al., 2010). The special issue covers topics that include (i) the monitoring of flash flood-related processes, (ii) regional analysis of flash flood regimes, (iii) representation of space–time and process variability in flash flood models and (iv) hydro-meteorological models for flash flood forecasting and warning.

This paper provides a review of the work conducted in HYDRATE with a special emphasis on how this body of research can contribute to guide the policy-life cycle concerning flash flood risk management. Such effort requires new knowledge to design policy implementation and development of indicators to measure the progress towards such objectives (Quevauviller, 2010).

2. Towards a characterization of flash floods in Europe

Observational difficulties of flash floods, barriers in hydrometeorological data transfer (Viglione et al., 2010a) and lack of a comprehensive archive of flood events across Europe hinder the development of a coherent framework for analysis of flood climatology, hazard and vulnerability at the pan-European scale. Among the few studies with a continental view, Barredo (2007) reports a catalogue of the major flood events since 1950–2006 in the European Union. In his study, Barredo characterized major floods in terms of casualties and direct damages. Twenty-three out of the forty-seven events listed in the catalogue are classified as flash floods, and are mainly localised in Italy, Spain and southern France. Flash flood events are also reported in Germany, Belgium and UK. In spite of the smaller areas impacted by these events, flash floods caused 2764 fatalities – i.e., 52 casualties per year in average, which is close to the annual statistic reported for the US by Ashley and Ashley (2008). The number of flash flood-related fatalities represents 40% of the overall casualties reported in the study, largely exceeding river floods (18%), and being second only to storm-surge floods (42%). Fatalities due to storm-surge floods concentrate into three extreme events that occurred from 1953 to 1962 on coastal regions of northern Europe, whereas flash-floods have been reported over the wider period (1950–2006) and across the whole European region. It should be noted that, given the focus of the study on major events, flash flood casualties were likely underestimated by Barredo (2007).

Gaume et al. (2009) analyzed the date of occurrence and flood peak distribution of flash floods from an inventory of events that occurred in selected regions of Europe over a 60 years period (from 1946 to 2007). The archive report data from both instrumented and ungauged basins. In contrast to Barredo (2007), the archive used by Gaume et al. (2009)

includes a substantial number of events from Eastern European countries. These authors noted a seasonality effect on flash flood occurrence, with events in the Mediterranean and Alpine-Mediterranean area (which includes Catalonia, Crete, France, Italy and Slovenia) mostly occurring in autumn, whereas events in the inland Continental region (Austria, Romania and Slovakia) commonly occur in summer, revealing different climatic forcing. Consistent with this seasonality effect, the spatial extent and duration of the events is generally smaller for the Continental floods with respect to those occurring in the Mediterranean area. Finally, Gaume et al. (2009) outlined that the flash flood regime is generally more intense in the Mediterranean area than in the Continental area of Europe. Findings by these authors are supported by the work Parajka et al. (2010), who analyzed the differences in the long-term regimes of extreme precipitation and floods across the Alpine-Carpathian range (from France to Romania) using seasonality indices and atmospheric circulation patterns to understand the main flood producing processes.

Building upon the investigation by Gaume et al. (2009), Marchi et al. (2010) recently examined in more detail the control exerted by watershed physiography and channel network geometry on flood response, and extended the analysis to the runoff coefficient and the response time. Owing to the requirement of high-resolution data, in particular high-resolution space–time rainfall, Marchi et al. (2010) focused on twenty-five major flash floods that occurred in Europe since 1994 (Fig. 1). In contrast with the work by Gaume et al. (2009), Marchi et al. (2010) focused on major events characterised by rainfall return intervals larger than 50 years (in some cases the return intervals exceeded 500 years). Rainfall duration in those cases range from 1 to 26 h, whereas catchment areas ranged from 20 km^2 to slightly more than 1000 km^2 (Fig. 2). Fig. 2 also shows that flash floods are essentially associated to Mesoscale Convective Systems, consistent with the criteria of Orlanski (1975). The main results from this study are summarised below.

2.1. Flash floods as ungauged extremes

The relationship between the catchment area and the unit peak discharge (i.e., the ratio between the peak discharge and the upstream catchment area) was investigated plotting the data in a log–log diagram and analyzing the envelope curve. When data from all the regions are grouped together, the unit peak discharges exhibit a marked dependence on area (Fig. 3a). The envelope curve reported in Fig. 3 is as follows

$$Q_u = 97.0A^{-0.4} \quad (1)$$

where Q_u is the unit peak discharge in m^3 s^{-1} km^{-2} and A is the upstream area in km^2. The figure shows that the highest unit peak discharges correspond to events from the Mediterranean region. For small basin areas, the flash floods observed under Continental climate, namely in Slovakia, also attain high values of unit discharge, even though these unit peaks seem to decrease with upstream area in a faster way than for the Mediterranean events. This behaviour highlights the different space and time scales of the generating storm events. The values provided by Eq. (1) are much higher than those obtained by analysing a sample of European riverine floods (Herschy, 2002), thus pointing out the extreme intensity of runoff generation during flash floods. Fig. 3b shows that more than half of the cases, and 80% of the data for basins less than 100 km^2, were collected by means of post-flood surveys following the methodology described in Borga et al. (2008). These proportions identify the observational problem which characterizes flash floods, which is especially severe for the events characterized by smaller spatial extent. Overall, these observations point out the unique role of post-flood survey in flash flood analysis.

2.2. Flash floods are associated to orography

Flash floods are often associated to complex orography. Relief is important since it may affect flash flood occurrence in

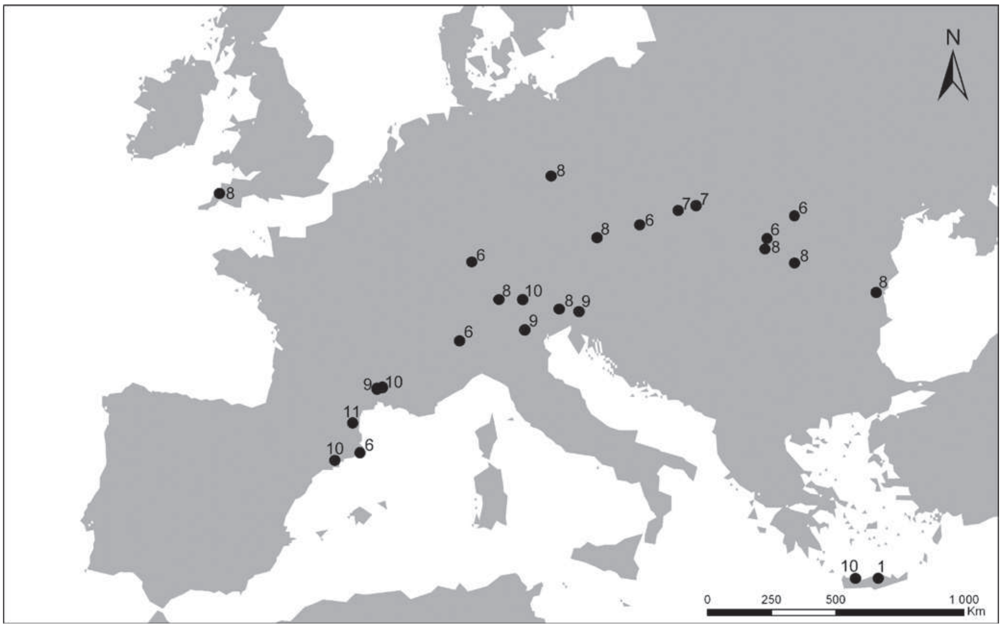

Fig. 1 – Location of studied flash floods; the numbers indicate the months of flash-flood occurrence.

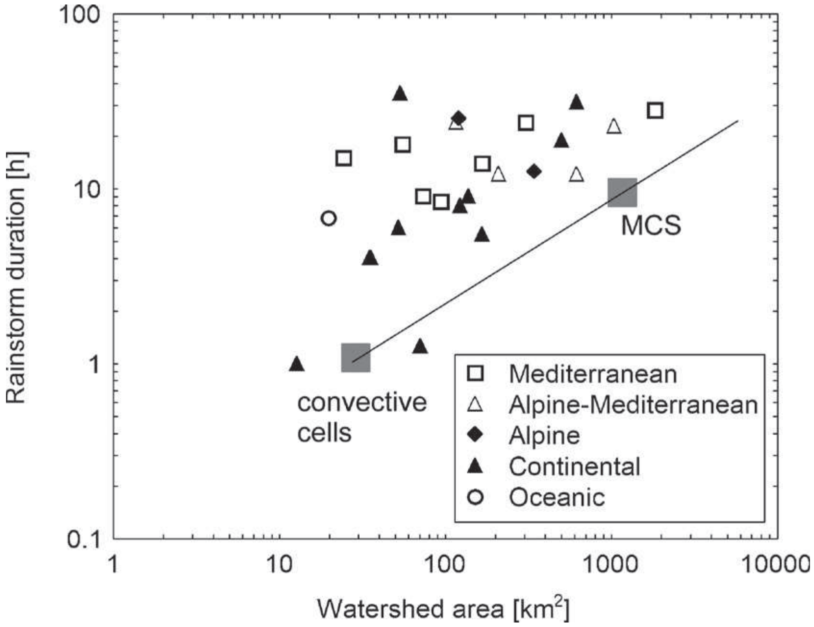

Fig. 2 – Spatial and temporal scales for the study flash floods. For each flood, the largest watershed and the corresponding rainstorm duration were considered. Scales of convective cells and MesoScale Convective Systems (MCS), shown as gray boxes, are taken from Orlanski (1975).

specific catchments by combination of two main mechanisms: orographic effects augmenting precipitation and anchoring convection, and topographic relief promoting rapid concentration of streamflow. However, major flash floods were also observed in areas either completely flat – such as the flood which impacted the metropolitan area of Venice in September 2007 (Rossa et al., 2010) – or only marginally influenced by orography – such as the major flash flood occurred in the Gard region in September 2002 (Delrieu et al., 2005).

2.3. *Impact of initial soil moisture conditions on flash flood occurrence and magnitude*

Marchi et al. (2010) examined the distribution of event runoff ratio (computed as the ratio between the event runoff and the causative precipitation) for the study events (Fig. 4). The analysis showed that runoff coefficients are rather low, with a mean value of 0.35. This agrees with earlier results obtained by Merz and Blöschl (2003) who reported that, based on their data from Austria, runoff coefficients are smallest for flash floods. Marchi et al. (2010) developed an antecedent precipitation index to assess the impact of initial soil moisture conditions on runoff coefficients. Three classes of antecedent saturation were considered: Dry, Normal, and Wet. Table 1 compares runoff coefficients in the three classes of antecedent precipitation index. Values of the runoff coefficient increase with moving from Dry to Normal and Wet antecedent conditions. The variability is highest within the ‘‘Dry’’ class, as expected, and decreases with increasing the initial soil moisture. The differences

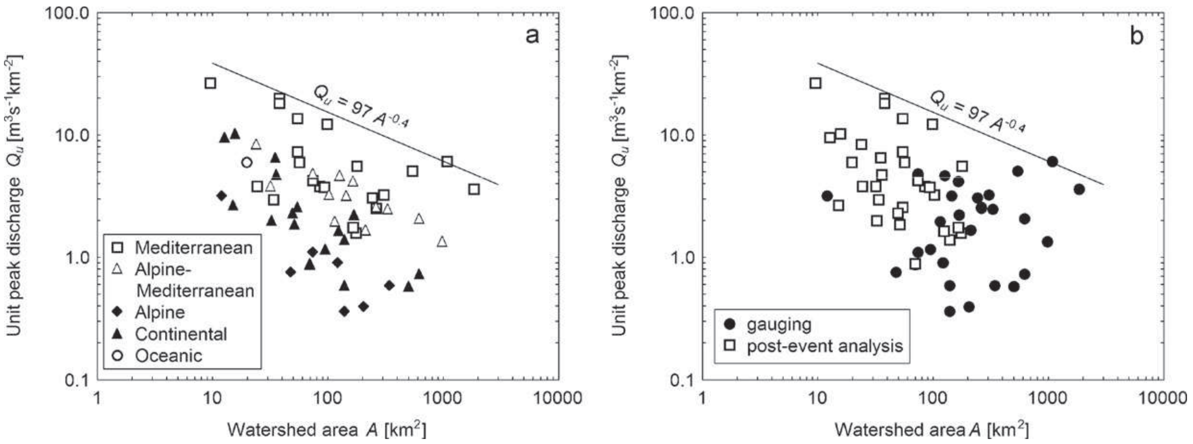

Fig. 3 – Unit peak discharges versus drainage areas; the envelope curve derived from Gaume et al. (2009) is also reported. (a) Climatic regions; (b) discharge assessment method.

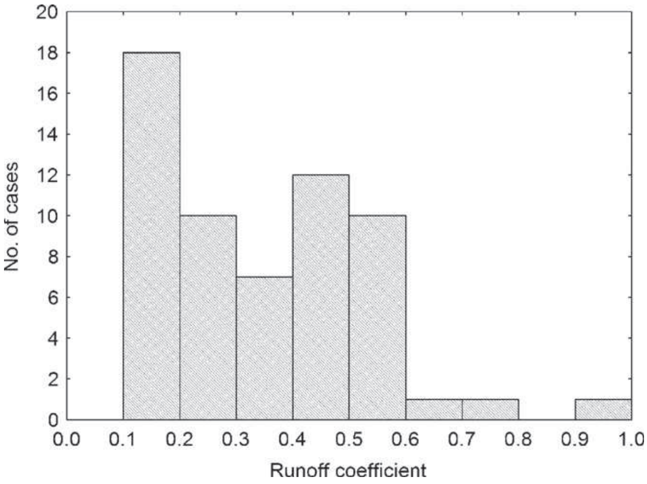

Fig. 4 – Frequency distribution of event runoff coefficient.

between Dry and Wet runoff coefficient distributions are statistically significant, showing that antecedent moisture conditions can play a significant role in determining land-surface response to extreme rainfall events. These results challenge the common wisdom that antecedent soil moisture is of little importance in determining the magnitude of extreme flash floods. Overall, this shows the need to account for hydrological processes and antecedent soil moisture conditions in the forecasting of flash floods. In the typical data-poor conditions which characterize flash flood forecasting and warning, surrogate indexes which can take implicitly into account the soil moisture initial conditions are extremely useful.

2.4. *Flash floods as geomorphic agents*

The occurrence of flash floods in complex terrain represents an important geomorphic agent. These floods are usually associated with widespread slope failures and flood power is sufficient to cause significant erosion and sedimentation in the floodplains (Marchi et al., 2009, 2010). HYDRATE focused on analysis of specific stream power as a key variable for the analysis of landforms modelled by the fluvial systems. Under flash flood conditions, this variable has been shown to peak in a narrow interval of catchment size ranging between 10 and 100 km^2, where it exceeds the threshold for major geomorphic changes in the channels. This is consistent with the field observations, which document the substantial geomorphic impact of these floods on channels and valley floors.

3. Advancing flash flood monitoring and forecasting

The consequences of the above observations are that forecasting of flash-floods depends critically on meso-scale storm forecasting capable to forecast deep convection events, and requires real time hydrological modeling. The technical requirements for a hydrometeorological flash flood forecasting system include (Collier, 2007): a remote sensing based (radar, satellites) precipitation detection system, a numerical weather prediction (NWP) model, capable to provide short-range Quantitative Precipitation Forecasts (QPF), and a hydrological-hydraulic forecasting model, capable to forecast the stream response from the rain input over a wide range of scales. These requirements are similar to those of more common riverine flood forecasting systems. However, some features characterise flash flood forecasting with respect to riverine flood forecasting and point out to their larger uncertainty (Siccardi et al., 2005). These are: (1) the short lead time and the challenge of forecasting convection; (2) the need to provide local forecasts, which means that, on one hand, the rainfall must be monitored and forecasted on a wide range of space/time scales, and, on the other hand, every tributary – generally ungauged – within a wide region can be considered as a potential target for flash flooding. Finally, flash flood forecasting and warning needs to be integrated into risk management strategies to realise its potential. Selected major advances by HYDRATE on extreme rainfall monitoring and nowcasting, flash flood forecasting and risk management are summarised below.

3.1. *Extreme rainfall monitoring by use of weather radar*

As shown above, flash floods are often associated with complex orography. Radar-rainfall estimation in this setting is complicated by ground returns and signal loss associated with beam blockage (Pellarin et al., 2002). An additional problem is that orographic storms may differ from storms forming away from terrain in terms of microphysical and dynamical properties (Smith et al., 1996). Finally, very few raingauges are generally available for radar raingauge comparison, including merging, uncertainty assessment (Germann et al., 2009) and optimization purposes. Kirstetter et al. (2010) illustrated the development of a comprehensive system of integrated procedures for the estimation of extreme rainfall rates by means of networks of C- and S-band radar. Furthermore, experiments were conducted with an X-band dual-polarization radar, showing the potential of such light-configuration systems to supplement conventional radars for short range application (e.g., 30 km) in mountainous terrain where the radar visibility may be low (Anagnostou et al., 2010).

Table 1 – Summary statistics of runoff coefficient for different antecedent wetness conditions.

Antecedent wetness class	No. of cases	Mean	Standard deviation
Dry	17	0.31	0.20
Normal	30	0.35	0.17
Wet	11	0.40	0.13

3.2. Radar data assimilation into NWP

Short-range precipitation forecasts have until recent years mainly been based on extrapolation techniques, and indeed, work continues to improve such techniques. Even though these approaches have shown some success (Berenguer et al., 2005; Vivoni et al., 2006), extrapolation techniques may fail to develop convection in new areas and to describe cell splitting and decay, which often control flash flood dynamics (Collier, 2007). The recent introduction of a new generation of NWP models capable to simulate, and potentially forecast, deep convection events explicitly offers the prospect of producing useful forecasts of convective storms on scales applicable for flood prediction. Rossa et al. (2010) examined the potential of radar-data assimilation on convection-permitting numerical weather prediction (NWP) for extending the forecasting lead time for flash flood events. By considering the 26 September 2007 Venice-Mestre flood case, they showed that radar rainfall assimilation had a very large impact on the forecasting, featuring a very efficient drying of mis-placed precipitation and excellent triggering of the observed convection, especially the main, flash flood producing mesoscale convective system. For the case study, assimilating radar rainfall into the NWP model afforded an extension of lead time by 3 h.

3.3. Flash flood forecasting

HYDRATE focused on developing (i) diagnostic methods, which aim to assess the potential for flash flood at the regional scale, based on analysis of current soil moisture status, and (ii) methodologies of application of distributed hydrologic models which are particularly suitable for flash flood forecasting and warning in ungauged basins. Norbiato et al. (2008, 2009) have demonstrated the good skill of procedures based on combining the Flash Flood Guidance approach and a method of model-based threshold runoff computation to improve the accuracy of flash flood forecasts at ungauged locations (FFDI – Flash Flood Diagnostic Index). An important aspect of threshold-based approaches is that these methods permit assimilation of local information, concerning both precipitation and streamflow or slope instability (Blöschl, 2008). While in meteorological forecasts, computer based generation of uncertainty products is often considered essential in communicating uncertainty to the public, for flash floods the assessment of the local situation matters most. In HYDRATE, this led to a strong research focus on the dominant runoff generation processes and on the aggregation and scale effects on distributed hydrological modeling under flash flood conditions (Anquetin et al., 2010; Braud et al., 2010; Sangati et al., 2009; Viglione et al., 2010b,c; Zanon et al., 2010; Zoccatelli et al., 2010).

3.4. Flash flood hazard assessment

New techniques for flash flood hazard assessment at the regional scale have been developed which benefit from the availability of data collected from post-flood surveys. This approach is exemplified by the work of Gaume et al. (2010), which provides a method for using major flash flood events that occurred at ungauged catchments to reduce the uncertainties in estimating regional flood quantiles. The method is based on standard regionalization methods assuming that the flood peak distribution rescaled by a site dependent index flood is uniform within a homogeneous region.

3.5. Preparedness and flash flood risk management

Short available time for hazard anticipation requires preparedness and response management by organisations and people (Faulkner and Ball, 2007). Preparedness structures response to events well in advance by establishing mechanisms for rapid and orderly action which limits impacts. Official and unofficial warnings, including self-warning as a result of personal observations of environmental and hazard signs, are important for flash flood management and must be considered when developing preparedness strategies.

Creutin et al. (2009) focused on the social response time for different social actions in the course of two well studied flash flood events which occurred in France and Italy. The event management activities were broadly characterized into three types according to their main objective (information, organisation and protection). This cycle of activities was assumed to be performed at three levels of social groups, namely individuals, communities and institutions. Results from the study led to question the common idea of a bulk reaction time of a community taken as a whole. It appears that a myriad of individuals and groups are reacting with different characteristic times at different levels of ‘‘self-organization’’. The raising of informal groups and networks during disasters is a well-known phenomenon (Quarantelli, 2008), which should be analyzed and positively considered by emergency managers as a contribution to the preparedness of a community.

4. Analysis of the mechanisms and barriers which limit the access to hydrometeorological data in Europe

As a part of HYDRATE, a specific effort addressed the analysis of the mechanisms and barriers which limit the access to hydrometeorological data across Europe and to understand the reasons and motivations for these barriers (Viglione et al., 2010a). This is a significant factor negatively affecting the development of a cohesive, freely available database of flash flood events at the European scale. The investigation aimed to provide indications for a more effective data policy in hydrometeorology, indicating where are the main perceived blockages to assist in policies that may address them. In an attempt to identify patterns of data policy and data exchange perceptions across Europe the data were stratified in: data providers and data users; type of institution (research, industry and administration); country (West and East Europe); and type of data (streamflow, precipitation, radar, geospatial, others). In an effort to provide a broad coverage of the European institutional and organizational frameworks, the survey was conducted for all European countries. Different types of barriers and reasons for barriers were identified, based on literature analysis and discussions within the HYDRATE project members. The barriers considered are *legal*, which includes licensing of data; *economic*, which includes pricing of the data; *practical*, such as excessively long delivery times or inconvenient data format (e.g., data provided in paper format only). The reasons for the barriers are *economic*, such as when data providers have to cover some of the expenses related to the data by earning an income from selling them, *conflict of interest* (such as when providers sell their products based on the data); and *misuse awareness* (such as redistribution of the data by the data users).

The study has outlined the significance of economic barriers in the data transfer process. Whereas the ''free access'' model follows the example of the United States, European countries tend to operate various schemes of differential charging of data, which is an effective regulation instrument in terms of use and access to data. Where the cost of data and its inherent value is becoming apparent in this way, cash scarce programmes and participants cannot afford research. In a drive for the commercialization of services, costs emerge as an effective barrier to access hydrological data. This has significant impacts both inside Europe, and outside Europe, since European data policies are often used as a template for developing data policies in developing countries, where this type of barrier may inhibit research on vital hydrological topics. This shows the urgent need of pan-European studies on the economics of the services of data collection, archiving and transferring (including economics of the hydrological information). Different options for funding the provision of hydrological services and for charging for the information provided should be described and evaluated.

5. Implications for flood risk policy: recommendations and feedback from end users

The science output of HYDRATE, summarized selectively in this work, may play an important role in the various phases of flood risk management policy. With the preparation and implementation of the EU Flood Directive, the notion of integrated flood risk management now tends towards a change of policy from one of flood defence, to flood risks being managed but not eliminated. Extending the concept of flood risk management to flash floods faces a number of challenges, which give raise to a number of recommendations, which were discussed with end users (including emergency planning, private end users and risk receptors) at four specific meetings held in Italy, Slovenia, Germany and Romania. The meetings were organized in communities which were recently impacted by flash floods, in order to collect feedback and responses specifically qualified for flash flood hazard and vulnerability.

5.1. *Data requirements for flash flood risk management*

Given the current difficulties in monitoring flash floods, the organization of actions aimed at improving the observation and monitoring capability of these events plays a critical role. Standard use of post-flood survey is recommended to gather flood response data (flow types, flood peak magnitude and time, damages, social response) with the objective to advance understanding of the causative processes and improve assessment of both hazard and vulnerability aspects (economical, social, ecological, etc.). The standardization of methods and techniques for post-flood survey is also instrumental in creating a cohesive European-wide catalogue of flash floods. These data set may prove invaluable to extend flood frequency estimation at scales that are usually ungauged, as shown by Gaume et al. (2010) for flash floods and by Merz and Blöschl (2008) for extreme floods. This type of information expansion is particularly important in small catchments, both because fewer and shorter records tend to be available than in larger catchments and because the flood processes are more amenable to analysis than in larger catchments where the regional combination of controls can be relatively more important. A key point made by the end users concern the need to extend the post flood data gathering methodology to collect observations concerning damage and vulnerability characteristics.

Estimation of extreme rainfall rates by weather radar at the appropriate time and space scales is the cornerstone of flash flood analysis and forecasting (Borga et al., 2002). However, HYDRATE has shown the difficulties posed by flash flood generating storms to current radar technology, particularly at C-band. After definition of European standards, the hydrologic visibility of national weather radar networks should be carefully checked and homogenized in order to provide reliable monitoring of extreme, localized storms. Furthermore, a European-wide assessment of new radar technologies, including networks of X-band dual-polarization radar, should be carried out under flash flood conditions to supplement conventional radars for short range applications.

To encourage the free exchange of data, certain regulations at the EU level would be useful for sharing the data, particularly in the context of the Water Framework Directive and the Flood Directive. Transfer of hydrological information should be embedded in an information feedback cycle which provides benefits for both the data providers and the data users. Governments and hydrological services should be informed about the benefits of shared information and about the value-added benefit which can be derived from this. The interests of data providers and data users must be recognized and adequately embedded in a data exchange policy. The protocols for the transfer of information must be known to the public and be transparent to all participants. Feedback may be a significant motivator to provide information. Examples are the provision of feedback mechanisms about the use of transferred information and the obtained results. This feedback cycle may reduce the asymmetry between the perceptions of data users and data providers on the barriers to data exchange, and hence to encourage a more efficient access to the rich data legacy that exists in Europe. As the main limitation to share data is economical, different options for funding the provision of hydrometeorological data were considered together with the hydro-meteorological services associated to HYDRATE. As a result of this discussion, a recommendation was made that general taxation revenue should provide most of the funds for public good hydrometeorological data. This agrees with results from the analysis of the different funding and pricing options of hydro-meteorological services carried out by Freebairn and Zillman (2002).

5.2. *Flash flood forecasting and warning*

Due to local characteristics, the small spatial scale and the sudden nature, flash floods are best managed by local authorities with effective involvement of people at risk. However, flash floods are usually sufficiently infrequent in any given geographical area that it is difficult for the local forecasters and experts to develop an adequate experience base. Given the uncertainties affecting flash flood forecasts, experience remains an essential element for issuing effective warning and implement preparedness strategies. The implication of this observation is that there is an urgent need to develop methodologies and tools to share experience, methods and results among different communities, organization and institutions which may be exposed to flash floods. These actions should be integrated to combine bottom-up and top-down approach. This will afford full exploitation of local expertise and enhance the value of regional monitoring and forecasting centers.

Readily applicable methodologies such as the Flash Flood Diagnostic Index (FFDI), based on the Flash Flood Guidance, could provide a first element for creating a European protocol for flash flood forecasting and warning. The end user response to the introduction of the FFDI in the forecasting chain in Italy (Upper Adige River Basin; Norbiato et al., 2009) was encouraging. It was noted that the use of the FFDI promotes close collaboration between hydrologists and meteorologists by simplifying communication about the hydrological status of basins. Moreover, it allows the forecaster to ingest local precipitation information readily and to update warnings without the need to run complex hydro-meteorological forecasting chains. Finally, the application of FFDI to ungauged basins has been shown to result in a limited decrease of system performance. The tools could be easily extended to consideration of debris flows triggering.

The development of a common European protocol for flash flood forecasting has the added benefit to ease implementation of a European-wide verification of flash flood forecasts and warning. Verification is required to measure current performance and to establish a baseline to be used to quantify the effectiveness of future enhancements. Analysis capabilities should be developed to work on a scale compatible with existing products and services. Verification requirements should identify flash flood events which occur but are not predicted, as well as predicted events that do not occur. Demonstrated improvements in current methodologies will lead to improved flash flood forecasting service.

5.3. *Flash flood risk management and policy*

While flash flood warning systems can substantially assist in reducing loss to life and property, they need to be integrated into a more general framework of flood risk management. Other risk management tools are complementary to warning systems. Also, there will be instances when there is not enough warning time and people may not be reached or will ignore warnings. Similar to the forecasting and warning component, risk management should be based on a fully integrated approach which recognizes the specificities of flash floods. These include: (i) the difficulties to rely on traditional physical flood defence infrastructure; (ii) the multi-hazard nature of flash flood risk, particularly when it involves mountainous settings; (iii) the need to develop specific preparedness strategies which incorporate event management. The identification of flash flood risk areas should inform the risk management process. The difficulties of relying on flood protection works place emphasis on land-use planning and flood event management. It is important to combine these two steps of flash flood risk management into one synthesized plan to enable the sharing of information between land-use planning and water management/civil protection authorities and to exploit the synergies between these two management fields (Samuels et al., 2008). Flood risk management consists of systematic actions in a cycle of preparedness, response and recovery and this should also be reflected in land management approaches. Long term flash flood risk management needs to address the tensions between risk management and economic development. Embracing scenarios of the future (including climatic, demographic and socio-economic changes) within the decision making process is required to identify precautionary, sustainable and adaptable risk mitigation policies and strategies (EC, 2009). Given the unique characteristics of flash floods and the large uncertainties affecting the long term risk assessment, a specific framework should be developed for risk communication with local stakeholders (Faulkner et al., 2007). Accounting for the multi-hazard nature of flash floods is particularly important. Often, flash floods, landslides and debris flows occur in conjunction which may cause amplification of the hazard – for instance, by inducing drastic changes in stream bed morphology during flash flood events. However, mapping of flood risk zones, which is an essential element in many national legislations, is generally based only on flood hazard assessment (Neuhold et al., 2009). There is therefore a need to develop a multi-risk approach which can tackle possible ‘‘simultaneous’’ and ‘‘cascade’’ effects due to coincident, or induced, occurrence of flash floods, landslides and debris flows that amplify the risk in some areas, and may be not accounted for by single hazard estimations. An approach towards such a development should be taken by the EU Directive on Floods, accordingly with the recommendations provided by the Working Group F on Floods of the Common Implementation Strategy. Also lacking are widely accepted methodologies for quantifying flood damages which integrate loss of human lives. This is a particularly delicate policy area as valuing life has major ethical implications. Still, multidisciplinary work along these lines is needed as pointed out by Jonkman and Vrijling (2008).

Preparedness measures need to be structured in accordance with the characteristics of flash floods (e.g., compressed timescales; short to negligible warning lead times; immediate threat to life as well as property; requirement for refuges and safe places; spontaneous and efficient organizational response requirement). Although valuable experience and knowledge has already been gained in flash flood locations about how best to set up preparedness, it is recognised that these locations still present challenging lacks. A key point made by end users concerns many flood preparedness methods and tools, which are designed for too loose timescales and less severe conditions (Drobot and Parker, 2007). An additional challenge for professional agencies is to fully integrate ‘risk’ as formulated and predicted by the scientific community into the more uncertain setting of an often binary management decision (Drobot and Parker, 2007).

An integrated approach to managing flash floods is essential and this should be reflected in the relevant policies. Integration needs to occur across a range of fields: (i) integrating the scale of actions to combine bottom-up and top-down approach. This will exploit both local expertise and enhance community acceptance in a participatory framework as it will be able to build on regional information and strengthen the networking of flood managers across Europe. (ii) Integrating various management strategies including structural measures such as retention basins and non-structural measures such as land use zoning and flash flood warnings. A best-mix of such strategies, depending on the local situation, is needed for optimising flash flood management. (iii) Integrating the management of all relevant natural hazards including flash floods, landslides and debris flows in a particular area or region. A holistic approach to emergency planning and management is preferable to a hazard-specific approach. In all types of management strategies, forecasts, early warnings and response play a key role as a primary step to mitigate the social and economic impacts of flash floods.

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